

TECHNICAL SPECIFICATIONS AND QUALITY CONTROL PROCEDURES FOR REDUCING THE UNCERTAINTY IN PV INSTALLATIONS: RESULTS OF THE FP7 PROJECT PVCROPS

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ABSTRACT: PVCROPS (PhotoVoltaic Cost rēduction, Reliability, Operational performance, Prediction and Simulation) is a project within the European Framework Programme 7 whose objectives are: improving the performance, reliability and lifetime of PV systems; reducing the cost of PV systems; and enhancing the integration of PV into the grid. The main way to reduce the initial costs of a PV installation involves an optimal design and subsequent construction. As a consequence, this optimization leads to a higher performance and to a lower levelized cost of electricity from PV. PVCROPS Work Package 2 and Work Package 9 have been conceived to achieve some of these objectives by proposing both an optimization of the design, to avoid undesirable initial mistakes that can make more expensive the cost of the installation, and a quality control of PV systems, to ensure the final installation matches the one designed initially and that it is able to overcome production requirements. This paper presents one of the main results of these work packages: a document that reflects the accumulated experience in the field by the PVCROPS team about actual PV installations and which contains, first, a general proposal of technical specifications for grid-connected PV systems and, second, the corresponding quality control procedures to check if the installation fulfills the technical specifications previously established. This document has also a report about a comparison between available PV energy performance models and a proposal about how to face the hot-spot problem within commercial frameworks.

Keywords: Technical specifications, quality control procedures, cost reduction, plant design, performance models, hot-spots.

1 INTRODUCTION

Large grid-connected PV plants have become an interesting financial product all around the world [1]. So, as for any financial product, a key point is to ensure that profitability of the PV installation is high and its risk of failure is low: the higher the yearly energy production and the lower its uncertainty, the more attractive is the project. A way to guarantee the quality of the installation and make more attractive the project involves an optimal design, an optimal construction and an optimal maintenance. This optimization leads to a higher performance and, therefore, to a reduction of the initial cost of the PV installation; that is, a decrease of the levelized cost of electricity from grid-connected PV systems.

Nevertheless, most of the commercial software for energy yield forecast [2] and international standards [3] [4] to check the quality of the installation do not take into account the bankability of a PV installation: they treat PV systems only from the technical point of view and they do not establish proper links between the technical and the financial issues (not only those related to the incomes due to the energy production). More and more it is needed connecting properly these two aspects when an analysis of the PV installations is required and later, once they are built, it is needed to determine who is the responsible when there is an operation of the system below the expected one: the module manufacturer, the inverter manufacturer, the designer, the constructor

and/or the operation and maintenance staff.

PVCROPS (PhotoVoltaic Cost rēduction, Reliability, Operational performance, Prediction and Simulation) is a project [5] within the European Framework Programme 7 which addresses this lack: it has developed a free software for energy yield forecast called SISIFO [6] that relies just on the information that should be guaranteed by manufacturers and it has also drawn up a document [7] related to the technical specifications and quality control procedures which links technical and financial aspects. These links make more attractive and sure the investment on a PV installation because they describe how to implement it and how to test it. Besides, they allow establishing the responsible for a possible under performance.

The document that is presented in this paper shows a general proposal of technical specifications and quality control procedures for grid connected PV plants ready to be easily adapted and included in contractual agreements. Both, technical specifications and quality control procedures are linked to reduce the uncertainty of the final energy yield forecast of a PV plant and, as a consequence, to make safest and more attractive to invest in this kind of projects. This document reflects the accumulated experience in the field by the PVCROPS team about actual PV installations, whose objectives are improving the performance, reliability and lifetime of PV systems so as reducing their cost.

2 CURRENT TECHNICAL QUALITY ASSURANCE PROCEDURES FOR PV SYSTEMS

Before a grid-connected PV installation is constructed, the system should have been designed and its yearly energy production which is going to be injected into the grid along its entire lifetime should have been simulated. That is, some expectations are created taking into account the specific climate of the location and the technical characteristics of PV devices, mainly PV modules and PV inverters.

As most of the PV installations are developed under "Project Finance" schemes (the energy production of the plant once it is constructed is the guarantee to recover the investment), "Due Diligence" procedures are compulsory in order to look for assuring the technical quality of the system. So, the objective of these procedures should be to check if the PV installation constructed fulfils the expectations that have been created in its design phase. Because of that, addressing the bankability of PV projects, through the modelling of its energetic yield followed by on-site measuring campaigns, has become a common PV engineering task [8].

Disregarding the evolution of the operation conditions (because no one can be responsible for future weather evolution), the actual performance of the PV system depends on the technical quality of the PV devices (modules, inverters, wires, fuses and fuse holders, switches, etc.) and on the technical quality of the construction (proper foundations, structures of high quality with suitable separation, good cabling, safe buildings and fences, etc.).

Nevertheless, till the date a not negligible quantity of quality control procedures over real PV installations uses to be restricted to: check if the PV devices delivered comply with the international standards (manufacturing procedures have the proper certificates [9] [10] [11] [12] [13]); test at independent laboratories a representative PV module sample before installation in the field and comparison with corresponding "flash-list" data for controlling the power P^* delivered by the PV module manufacturer; check if the PV installation complies with the "Minimum requirements for system documentation, commissioning test and inspection" [3]; and to obtain the Performance Ratio, PR (defined in international standards [14]).

Unfortunately, none of the previous procedures assure a subsequent good performance of the system, nor allow establishing clearly who is the responsible in case the operation of the system is below the expected one.

For example, PV modules can have certifications of have been manufactured according to international standards and its power can be satisfactorily tested at independent laboratories before its installation in the field. But later the modules could show undesirable losses due to LID (Light Induced Degradation) or PID (Potential Induced Degradation), which are not currently addressed by the international standards. So, it is recommended testing the representative modules sample not only "as received" but also after an exposure above 60 kWh/m^2 . That assures the PV module reaches the PV plant in proper conditions and also provides information for estimating real LID rates. Besides, PV efficiency varies with temperature and irradiance. Manufacturers provide the temperature coefficients and the efficiency reduction from STC to 200 W/m^2 at module's datasheet, but this information is sometimes of doubtful

representativeness. Therefore, it is also recommended testing the performance related to the variation of temperature and irradiance of the representative PV module sample selected. Moreover, it is worth considering testing also PV modules propensity to PID. That allows detecting possible performance irregularities before PV modules reach the field and provides more certain information than datasheets. Thanks to all these measurements the yield assessment can be updated with this experimental data, which reduces the uncertainty of the energy forecast.

Regarding the requirements for system documentation, commissioning test and inspection [3], the international standard literally warns that the verification of the module or array performance is outside its scope. So, this information is useful as an evidence of right installation of the system, but this not assure a good performance.

Finally, the PR is not a good indicator of the system because it lumps together avoidable and unavoidable losses. The first ones are due to technical imperfections deriving on real performance below the nominal characteristics reported by the equipment manufacturers (underrating, mismatching, under efficiency, etc.), while the second ones are intrinsic to the functioning (thermal and irradiance efficiency losses) or to the design (shades and inverter saturation, the last due to large DC/AC ratios) of the PV plant. Therefore, only avoidable losses are really related to the technical quality of the PV plant. So this mere PR is adequate for qualifying the technical quality when full year periods are considered. This is because, for a given PV plant and site, the PR value tends to be constant along the years, as much as the climatic conditions tends to repeat. But when sub-years periods are considered, the PR dependence on unavoidable and time-dependent losses requires corresponding correction in order to properly qualify the technical quality of a PV plant. Otherwise, the qualification result of a same PV plant varies with the climatic conditions of the qualification period, which seems contrary to the common sense. These losses are the ones derived from the efficiency variation with temperature and irradiance, from intrinsic to PV design phenomena (shades and inverter saturation) and from possible angular and spectral response differences between the PV array and the irradiance sensor. A convenient way of doing such correction is to consider the so-called Performance Ratio at Standard Test Conditions, PR_{STC} , which can be properly understood as the PR of the same plant but corresponding to a hypothetic period with the PV array permanently kept at STC [8]. Besides, in order to reduce as much as possible the uncertainty related to sensors of irradiance (angular, spectral and dirt responses) and temperature (non-homogeneous temperatures distribution inside the PV module), we recommend using reference modules in order to measure effective irradiance and cell temperature. These devices, which are not commercially available, must be specifically prepared which means stabilization followed by calibration [15].

3 PVCROPS TECHNICAL QUALITY ASSURANCE PROCEDURES FOR PV SYSTEMS

The PVCROPS project has proposed some solutions to address the lacks we have presented previously. It has developed a free software for energy yield forecast called

SISIFO [6] which relies just on the information that should be guaranteed by manufacturers and it has also drawn up a document [7] related to the technical specifications and quality control procedures which links technical and financial aspects. This document has also a study that compares available PV energy performance models and the one selected by SISIFO, that concludes that a simple model that relies on manufacturer's information is so accurate than others more complex, as well as a proposal about how to face the hot-spot problem within commercial frameworks, a reference that is very valuable nowadays in the PV sector.

Besides, PVCROPS project has designed and developed some testing kits to execute the quality control procedures proposed [16].

3.1 Energy yield forecast software.

First of all, the PVCROPS project has developed a PV simulation software called SISIFO (it is free available also in the PVCROPS webpage [5]). SISIFO relays on a simple PV module model based on the variation of its power with the irradiance and the temperature which combines both a good accuracy and a good adherence to manufacturer datasheet information:

$$P_{DC}(G_{ef}, T_C) = P^* \frac{\eta(G_{ef}, T_C)}{\eta^*} f_{DC}$$

where

$$\frac{\eta(G_{ef}, T_C)}{\eta^*} = \frac{G_{ef}}{G^*} [1 + \gamma \cdot (T_C - T_C^*)] [a + b \frac{G_{ef}}{G^*} + c \cdot \ln \frac{G_{ef}}{G^*}]$$

In these equations, the superscript * means STC; P^* is the nameplate DC power obtained from the manufacturer's information; η means efficiency; G_{ef} is the effective global solar irradiance in the plane of the array; G^* is the global solar irradiance at STC ($G^* = 1000 \text{ W/m}^2$); T_C is the cell temperature; T_C^* is the cell temperature at STC ($T_C^* = 25^\circ\text{C}$); γ is the thermal losses coefficient (a value which is always found at manufacturer datasheets); the three parameters, a , b and c , describe the efficiency dependence on irradiance; and f_{DC} is a coefficient that lumps together all the additional system losses in DC, e.g., technology-related issues, wiring, soiling and shading.

This equation properly defines the performance of a PV array with high accuracy as demonstrated by other authors [17] (and as it has been reviewed in one of the annexes of the document [7]).

It is interesting to note that concerned parameters P^* , γ , a , b and c are not only given at the information datasheet, but also considered as a part of the design qualification international norms (a , b and c are obtained from module power related to three irradiance values, which must also be found at datasheets, providing they comply with international standards [9] [10] [18]). So, this is an advantage of this model in relation to other commercially available software packages [2], most of them describing the electrical behaviour of the PV modules by means of the so called 5 parameters one diode model equation. The required input data for the one diode model (series and shunt resistance, photocurrent, saturation current and diode quality factor) are not found at the PV manufacturer datasheets ("...these data are key parameters of the model, and should be part of the

module's specifications in the future" [19]). Instead, they are derived from certain software authors assumptions from I - V curves measured on particular specimens at independent testing organizations, which entail a risk of breaking-off of the responsibility chain.

The AC power at the output of the PV system from this DC power at the inverter entry is

$$P_{AC} = P_{DC} \eta_{INV} f_{AC}$$

where P_{AC} is the AC power output of the PV array, η_{INV} is the efficiency of the inverter (which can be estimated from several values characteristics of its load curve and also can be measured on site by recording simultaneously P_{AC} and P_{DC} values with a high accuracy watt-meter during a whole sunny day [20]), and f_{AC} is a coefficient that lumps together all the additional system losses in AC, e.g., technology-related issues and wiring.

Finally, the energy produced during a period of time T (a year, for example) is given by:

$$E_{AC} = \int_{t=0}^{t=T} P_{AC} dt$$

More information about the SISIFO software package can be found in the literature [6] [21] [22].

Thanks to all these measurements (P^* , γ , a , b , c and η_{INV}) the yield assessment can be updated with this experimental data, which reduces the uncertainty of the initial energy forecast.

3.2 Technical specifications and quality control procedures.

Then, PVCROPS has drawn up the technical specifications and quality control procedures which link technical and financial aspects of a PV installation. They are written in such a way that they can be almost directly applied in contractual frameworks or as a part of the technical requirements of an international tender dossier (they only have to be slightly modified to be adapted to the particular situation considered).

The technical specifications indicates what are the basic characteristics that a PV installation must submit related to: PV arrays; supporting structures; inverters; LV/MV transformers; monitoring and data acquisition; buildings and auxiliary services; grounding and lightning protection; safety and fire protection; and civil works. These technical specifications seek an optimization of the initial installation design to avoid undesirable initial mistakes that can reduce the final energy production of the PV installation and make more expensive its cost [23].

For example, some of the technical specifications related to inverters are: "In order to facilitate the acceptance tests, the inverter must include means (shunt, toroid, etc.) for measuring DC input current with accuracy of, at least, 0.5%. Such means must be duly certified and fully accessible during reception test"; "The so-called "European efficiency" of the inverters must be at least 0.95. This efficiency is given by the formula:

$$\eta_{EUR} = 0.03\eta_5 + 0.06\eta_{10} + 0.13\eta_{20} + 0.1\eta_{30} + 0.48\eta_{50} + 0.2\eta_{100}$$

where $\eta_5, \eta_{10}, \eta_{20}, \eta_{30}, \eta_{50}, \eta_{100}$ are the instantaneous power efficiency values at 5%, 10%, 20%, 30%, 50% and 100% load”.

Another example, now a technical specification related to monitoring and data acquisition is: “The sensors to measure the effective incident irradiance over the PV arrays, G_{ef} , and their cell temperature in operation, T_C , will be reference modules of the same manufacturer, type and model than the ones installed in the PV arrays”.

The quality control procedures establish which are the tests that should be done at different stages of building a PV plant until its first year of life: prior to installation (laboratory measurements); in the commissioning (on-field measurements); and after one year of routine operation (on-field measurements and based on the SCADA records). These quality control procedures seek to ensure that the final installation, first, matches the one designed and meets the technical specifications previously established and, second, try to check that is going to overcome the production requirements. These quality control procedures settle down the basis to reduce the uncertainty of the final energy yield forecast by testing the main devices of the installation, as well as proposing the best practices to reduce the uncertainty of the results from the individual tests. Besides, they report about how these devices have performed in comparison with the characteristics disclosed by manufacturers.

Going on with the examples shown previously, these are some of the quality control procedures which are linked to them: “The PV system characterization test principle consist on the simultaneous observation of the operating conditions –on plane effective irradiance (G_{ef}) and cell temperature (T_C)–, and of the power system response –inverter DC input power (P_{DC}) and inverter AC output power (P_{AC})–”; “The operation conditions G_{ef} and T_C will be recorded at least once per minute”; “In order to characterize the inverter, every set of values (P_{DC} , P_{AC}) will be translated to the corresponding set of values (η_{INV} , p)”; “ P_{DC} and P_{AC} must be measured with a high quality wattmeter”.

3.3 Testing kits.

Together to the technical specification and the quality control procedures, the PVCROPS team has designed and implemented different testing kits to perform these quality control procedures previously defined. These testing kits have been designed, assembled and finally tested in real PV installations to check their usefulness for the quality control of PV systems. Six testing kits have been proposed:

- A testing kit that allows evaluating the global performance of the PV systems as a black box and that reports if the final energy production is the proper one.
- Some testing kits that allows obtaining the I - V characteristic of PV modules/arrays, so the quality and the health of the PV modules/arrays can be evaluated [24] [25].
- A testing kit that allows knowing more in detail the behaviour of the PV modules (response of the module with variations of G_{ef} or T_C) [26].
- Some testing kits that allow knowing if the PV modules are prone to/affected by Potential Induced Degradation, a subject very important

nowadays in large PV plants [27].

- Some testing kits to check the thermal behaviour of PV modules in operation, which is critical for the reliability of the modules. Otherwise they will show a high-premature degradation (besides, there is an annex in the document of the technical specifications and quality control procedures which shows a research about hot-spots and an acceptance/rejection criteria of modules affected by this phenomenon) [28] [29].
- Some testing kits that allow obtaining a very accurate and detailed analysis of the PV installation, from the whole PV system performance, reporting clearly about anomalous situations in its operation, to the individual performance of PV arrays and inverters, reporting about the fulfilment of their actual characteristics related to the ones stated by the manufacturers [8].

All these testing kits have been assembled and used in real PV installations. The characteristics of these testing kits and the result of some measurements done with them in real PV systems are reported in the PVCROPS website [16].

4 SUMMARY

This paper has presented a part of the work done by PVCROPS project in order to reduce the cost of grid-connected PV systems, to increase its quality and, therefore, to get a higher yearly energy production, which leads to a lower LCoE. These objectives are met with an optimal design and subsequent construction. So, PVCROPS team has taken advantage of its experience on these kind of systems and has written a document which contains a general proposal of technical specifications for grid-connected PV systems and the corresponding quality control procedures to check if the installation fulfills these technical specifications previously established. These technical specifications and quality control procedures are totally linked, describing how to implement a PV system and how to test it in order to evaluate its quality. They have been drawn up in such a way that they can be easily adapted and included in contractual agreements. This general proposal is based on a free software for energy yield forecast (SISIFO) which relies just on the information that should be guaranteed by manufacturers. This way the uncertainty of the final energy yield forecast of a PV plant is reduced once the quality control procedures have been applied and, as a consequence, it is safer and more attractive to invest in this kind of projects because the responsible for a possible under performance is clearly defined and easier to detect.

The presented document has also two annexes: the first of them is a comparison between available PV energy performance models; the second one is a proposal about how to face the hot-spots problem within commercial frameworks.

Besides these technical specifications and quality control procedures, PVCROPS team has also designed, assembled and tested in real PV installations some testing kits which can be useful to perform the quality control procedures proposed.

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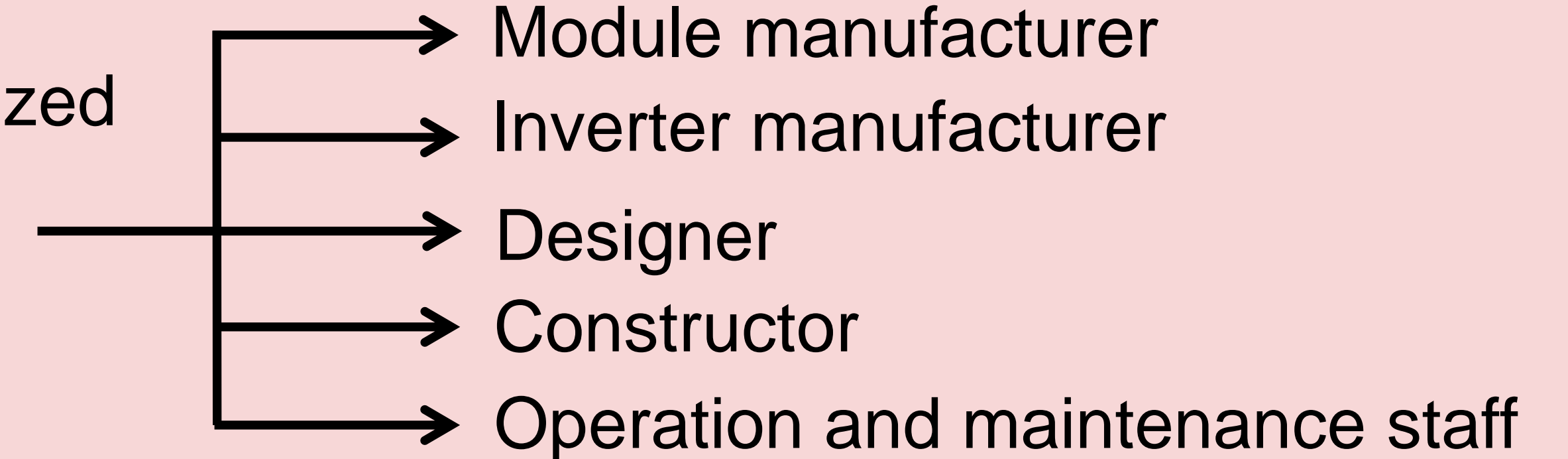
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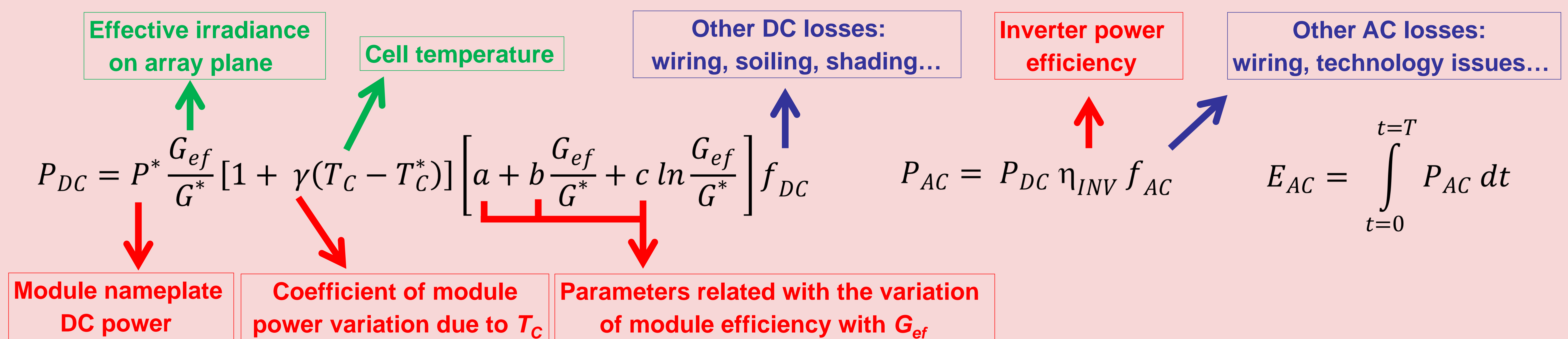
1. INTRODUCTION

- Large grid-connected PV plants have become an interesting financial product all around the world:
 - The annual energy production should be maximized
 - The uncertainty of the investment and the risk of failures should be minimized
 - The responsible for a possible under performance must be easily detected
- Technical and financial issues should be linked
- PVCROPS project has developed:
 - A free software tool for the energy yield forecast (SISIFO)
 - A general proposal of technical specifications and the corresponding quality control procedures to check if they are fulfilled
 - Testing kits to perform the quality control procedures



2. ENERGY YIELD FORECAST

- SISIFO is a free software tool (www.sisifo.info) to simulate energy production that uses **a model based on parameters guaranteed by the manufacturers**, **a baseline losses scenario** and **operating conditions**.



- More accurate estimation of energy and lower uncertainty if
 - G_{ef} and T_C are measured with reference PV modules of the same technology.
 - P_M^* , γ , a , b and c of a representative sample of modules are measured (better than datasheet)

3. TECHNICAL SPECIFICATIONS AND QUALITY CONTROL PROCEDURES

- The technical specifications (TS) report about how the PV installation must be implemented
- The quality control procedures establish the tests that should be done to ensure the PV installation meets the TS
 - G_{ef} and T_C measured from reference PV modules (same angular, spectral, thermal, dirt response) → **Uncertainty reduced**
 - PV modules not only characterized at STC (P_M^*), but also behaviour with T_C (γ) and with G_{ef} (a , b and c) → **Uncertainty reduced**
 - Analysis of PR at Standard Test Conditions (PR_{STC} , not site-dependent nor time-dependent) → **Uncertainty reduced**
 - Real behaviour of PV plant: DC power characterization, inverter efficiency, AC power response (actual losses scenario) → **Uncertainty reduced**

We are looking you forward in the parallel event (Thursday 17th Sept 13:20–18:30):

“PVCROPS: Novel solutions for a high PV penetration in EU electrical networks with lower LCOE”

(At 17:00: Quality control procedures for the bankability of PV plants: Software and Hardware solutions)